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MRL-R-1114

AR-005-225

AD-A200 045

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

MATERIALS RESEARCH LABORATORY

MELBOURNE, VICTORIA

REPORT

MRL-R-1114

THE EFFECT OF SHIP MOTION ON SHIP MAGNETIC SIGNATURE

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ABSTRACT

The effects of roll, pitch and yaw motions on a ship's magnetic signature are investigated. These three modes of rotary motion, assumed to be each simple harmonic, are treated as uncoupled and a dipole model representation is used to describe the ship's magnetization. Signatures are computed for a model ship assumed, for simplicity, to be bearing due magnetic North and compared with the steady-state signatures (for no rotary motion). Oscillatory magnetic field components result from these ship motions which decrease in significance, compared to the steady-state fields, as the observation point is moved further away from the ship's passage. These field deviations decrease more rapidly with abeam displacement than with depth. Variation with ship speed is more complicated and depends critically on the values assigned for the amplitudes, frequencies, and relative phases of the three modes of motion. In high sea states the magnetic signatures can vary considerably from those in calm seas with implications for magnetic-influence mine actuation.

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THE EFFECT OF SHIP MOTION ON SHIP MAGNETIC SIGNATURE

1. INTRODUCTION

A warship, which consists mainly of ferromagnetic material, is magnetized by the earth's field producing a localized magnetic anomaly. The movement of this anomaly, or irregularity in the environmental background field can be detected and used to actuate magnetic-influence mines (see ref. [1] for a simple discussion).

The magnetization of a ship can be approximated by a set of three-axis magnetic dipoles uniformly spaced along the midships line [2]. The magnetic anomaly at any point in space around the ship can be readily computed from the vector sum of the contributions from each dipole using the dipole field equations. The variation with time of the magnetic anomaly at a fixed position due to the passing ship can thus be calculated.

When the ship sails in a constant direction on a calm sea with a mirror-smooth surface ("sea state zero") the dipole vectors describing the ship's magnetization will be constant. Computation of the magnetic fields at an external observation point due to the moving ship is relatively straightforward. In reality, higher sea states are likely to be encountered with a range of differing wave heights, wave lengths, and periodicities. These will impart to the ship a complex oscillatory motion which to a first approximation can be considered as a combination of uncoupled roll, pitch and yaw movements. The effects of these movements on a ship's magnetic signature have potential implications for magnetic mine algorithm effectiveness.

In this report the effect of sea state on the magnetic field due to a passing vessel is investigated. It is assumed that the subject of the study is a heavy warship which will roll, pitch, and yaw freely about its centroid but will not undergo the translational motions of surge, sway, or heave to any significant extent.

2. EFFECT OF SHIP MOTION ON SHIP MAGNETIZATION

2.1 Description of Ship Motion and Magnetization

To reduce the complexity of the problem, the ship was assumed to roll, pitch and yaw independently in each axis. Each motion was assumed to be simple harmonic and could thus be described by a single amplitude and frequency. In reality these motions will be coupled so that, for example, the amplitude of the yaw motion may depend on the pitch of the ship. Furthermore there will be higher frequency components involved in the motions [3].

A freely moving object undergoing rotary motion normally has its centre of rotation coincident with its centre of gravity. For a surface ship the situation is different since it is partially submerged. When the ship rolls, for example, its **centre of buoyancy** (centroid of displaced volume) shifts horizontally and provides a righting moment to restore it to its upright position. For small oscillations, roll motion takes place about the **metacentre** which is the point of intersection of a vertical line through the centre of buoyancy and the original centre line [4]. However, to reduce the complexity of the calculations, it is assumed here that all the ship rotary motions take place about the ship's centre of gravity which lies on the waterline. Errors introduced by this approximation are of less significance than the errors involved in the dipole model representation of the ship's magnetization [2].

A left-handed coordinate system fixed relative to the sea bed is used as shown in Fig. 1(a). The X axis is positive from stern to bow along the ship's passage, the Y axis positive from starboard to port, and positive Z axis vertically downwards. The origin ($X = Y = Z = 0$) is assumed to be at the closest point of approach (CPA) of the ship's bow to the observation point ignoring the ship's pitching and yawing motions.

Since the motions are assumed to be simple harmonic, at time t the roll (θ), pitch (ϕ), and yaw (ψ) angles are given by

$$\theta = \theta_{max}\ sin(\omega_R t) \tag{1a}$$

$$\phi = \phi_{max}\ sin(\omega_P t) \tag{1b}$$

$$\psi = \psi_{max}\ sin(\omega_Y t) \tag{1c}$$

where θ_{max}, ϕ_{max}, ψ_{max} are the roll, pitch, yaw amplitudes and the ω terms are the angular frequencies. The roll motion is assumed to start in an anticlockwise fashion along the ship's trajectory, the pitch motion to start in an upwards movement and the yaw motion also to begin in an anticlockwise fashion viewed from above the ship's passage. These rotary modes of motion are shown in Fig. 1 (b). Initially at time $t = 0$ the angles θ, ϕ, and ψ are all zero from equations (1) so that all the motions are in phase.

Ship magnetization is described by a line of evenly-spaced, point, three-axis magnetic dipoles. Each dipole has orthogonal moments MX, MY, MZ and each of these has both a **permanent** and **induced** component so that, for example, $MX = MX_p + MX_i$ with the subscripts p and i denoting permanent and induced respectively. When the ship and thus the dipole array are rotated to a new orientation the permanent components will not vary. However since the ship's orientation with respect to the earth's magnetic field has changed, the induced components will vary with time. In the following sections the effects of roll, pitch, and yaw motions on ship magnetic signatures are discussed.

2.2 Effect of Roll Motion

When the ship rolls about its longitudinal (X) axis, the positions of the dipoles relative to an external observation point are unchanged; only the dipole moments are affected. Considering a three-axis dipole for which the total moments due to the permanent and induced components are initially MX, MY, and MZ, it is clear that the roll motion will not affect the MX moment. However the MY and MZ moments will alter as the ship rolls about its longitudinal axis.

It is assumed that the ship is bearing due magnetic North so that to a good approximation there is no induced athwartships magnetization [2] ($MY_i = 0$ and thus $MY = MY_p$). The dipole moments MY' and MZ' when the ship has rolled anticlockwise through an angle θ are given in the ship's reference frame by :

$$MY' = MY_p + MZ_i sin\theta \tag{2a}$$

$$MZ' = MZ_p + MZ_i cos\theta \tag{2b}$$

where the subscript p denotes the permanent components and MZ_i is the initial (unrolled) value of the induced vertical component. Since the ship bears North, only the vertical component of the earth's field can induce magnetization in the Y' and Z' axes. It is assumed that the ship is magnetically symmetrical about the longitudinal roll axis so that the magnetization induced in the vertical direction is constant. Now if $\beta = MZ_i/MZ_p$, then the rolled moments are given by :

$$MY' = MY + \frac{\beta MZ\ sin\theta}{(1+\beta)} \tag{3a}$$

$$MZ' = MZ\ \left[\frac{1+\beta cos\theta}{(1+\beta)}\right] \tag{3b}$$

The dipole moments projected along the initial unrotated axes are then :

$$XPole = MX' \tag{4a}$$

$$YPole = MY'cos\theta - MZ'sin\theta \tag{4b}$$

$$ZPole = MY'sin\theta + MZ'cos\theta \tag{4c}$$

2.3 Effect of Pitch Motion

From a magnetostatic viewpoint, pitch motion is more complicated than roll motion. Since the ship pitches up and down with simple harmonic motion the positions as well as the magnitudes of the dipoles vary with simple harmonic motion. Furthermore both the horizontal and vertical components of the earth's field contribute to the ship's magnetization since pitch motion occurs in the $X - Z$ plane.

Again assuming that the ship is bearing magnetic North, consider the case of the ship pitching up through an angle ϕ about its athwartships axis. As for roll motion the permanent dipole components are unchanged, but the induced moments depend on the orientation of the ship to the earth's field components. If HX and HZ are the local values of the horizontal and vertical components of the earth's field, the induced moments along the X and Z axes are given by

$$MX_i = C \times HX \tag{5a}$$

$$MZ_i = D \times HZ \tag{5b}$$

in the non-pitched position where C and D are constants. When the ship pitches, to a reasonable approximation the induced moments are given by

$$MX_i' = C \times (HX cos\phi - HZ sin\phi) \tag{6a}$$

$$MZ_i' = D \times (HZ cos\phi + HX sin\phi) \tag{6b}$$

assuming that each induced moment depends linearly on the earth's field component along each ship axis. Eliminating the constants C and D the induced moments may be written as

$$\begin{aligned} MX_i' &= MX_i \times (cos\phi - \gamma sin\phi) \\ &= uMX_i \end{aligned} \tag{7a}$$

$$\begin{aligned} MZ_i' &= MZ_i \times (cos\phi + sin\phi/\gamma) \\ &= vMZ_i \end{aligned} \tag{7b}$$

where u and v are introduced for convenience and $\gamma = HZ/HX$. Then from the relations

$$MX_i = \alpha MX_p; \; MZ_i = \beta MZ_p; \tag{8}$$

the moments along the rotated axes are given by

$$MX' = MX\left[\frac{1 + \alpha u}{1 + \alpha}\right] \tag{9a}$$

$$MZ' = MZ\left[\frac{1+\beta v}{1+\beta}\right] \tag{9b}$$

The dipole moments projected along the initial unrotated axes when the ship has pitched through ϕ are given by :

$$XPole = MX'cos\phi + MZ'sin\phi \tag{10a}$$
$$YPole = MY' \tag{10b}$$
$$ZPole = MZ'cos\phi - MX'sin\phi \tag{10c}$$

2.4 Effect of Yaw Motion

For yaw motion the vertical magnetization will remain constant since yawing occurs only in the $X - Y$ horizontal sea plane. As with pitch motion the relative positions of the dipoles will alter as the ship yaws. The induced longitudinal and athwartships moments for an anticlockwise yawing movement through an angle ψ are given by

$$MX_i' = MX_i cos\psi \tag{11a}$$
$$MY_i' = -\delta MX_i sin\psi, \tag{11b}$$

using the results in the Appendix for the induced athwartships magnetization in yawing motion ($MY_i = 0$ so MY_i' is determined from MX_i). Thus the new moments can be approximated as

$$MX' = MX\left[\frac{1+\alpha cos\psi}{1+\alpha}\right] \tag{12a}$$

$$MY' = MY - \frac{\delta\alpha MX sin\psi}{(1+\alpha)} \tag{12b}$$

$$MZ' = MZ \tag{12c}$$

where $\alpha = MX_p/MX_i$ as before. The moments projected along the original axes can be written as :

$$XPole = MX'cos\psi - MY'sin\psi \tag{13a}$$
$$YPole = MY'cos\psi + MX'sin\psi \tag{13b}$$
$$ZPole = MZ' \tag{13c}$$

2.5 Effect of Combined Motions

In general a ship will undergo roll, pitch, and yaw motions simultaneously. Combining equations (3), (9), and (12) the dipole magnitudes for a transformation through a roll angle θ, a pitch angle ϕ, and a yaw angle ψ become :

$$MX''' = MX \times \left[\frac{(1+\alpha u)(1+\alpha cos\psi)}{(1+\alpha)^2}\right] \tag{14a}$$

$$MY''' = MY + \frac{\beta MZ sin\theta}{1+\beta} - \frac{\delta\alpha MX sin\psi}{1+\alpha} \tag{14b}$$

$$MZ''' = MZ \times \left[\frac{(1+\beta v)(1+\beta cos\theta)}{(1+\beta)^2}\right] \tag{14c}$$

Since each set of equations (3), (9), and (12) has been derived independently with the assumption that the ship is bearing due magnetic North these expressions will only provide an approximation to the ship magnetization for the combined motions. To determine the moments projected along the initial coordinate axes, these moments must be successively projected from axes oriented at angles of θ, ϕ, ψ. Thus projecting through ψ gives the intermediate moments MX'',MY'', and MZ'':

$$MX'' = MX''' cos\psi - MY''' sin\psi \tag{15a}$$

$$MY'' = MY''' cos\psi + MX''' sin\psi \tag{15b}$$

$$MZ'' = MZ''' \tag{15c}$$

These values must be further projected through -ϕ to give :

$$MX' = MX'' cos\phi + MZ'' sin\phi \tag{16a}$$

$$MY' = MY'' \tag{16b}$$

$$MZ' = MZ'' cos\phi - MX'' sin\phi \tag{16c}$$

Finally projecting through -θ gives the dipole moments MX_r, MY_r, MZ_r projected along the initial axes

$$MX_r = MX' \tag{17a}$$

$$MY_r = MY' cos\theta - MZ' sin\theta \tag{17b}$$

$$MZ_r = MZ' cos\theta + MY' sin\theta \tag{17c}$$

2.6 Effect of Ship Motion on Dipole Coordinates

The pitching and yawing movements of the ship impart oscillatory motions to the dipole positions : relative to an external observation point the spacings of the dipoles will be alternately compressed and expanded. Since the magnetic field due to a dipole depends both on its moment and displacement, this dipole motion will add additional oscillatory components to the magnetic signature. These will probably only be of second order in comparison with the moment variation discussed in sections 2.2 - 2.5, but must be included for completeness.

In the ship's moving reference frame, the dipoles are spaced distance D apart with the first dipole at a distance $D/2$ from the bow. When the ship pitches through an angle ϕ the X and Z coordinates of the Ith dipole relative to the initial position of the ship bow are given by

$$X(I) = -D \times [NDIP/2 - (NDIP/2 - I + 0.5)cos\phi] \quad (18a)$$
$$Z(I) = -D \times (NDIP/2 - I + 0.5)sin\phi, \quad (18b)$$

where D is the dipole spacing and $NDIP$ is the number of dipoles in the array. Thus the X and Z dipole coordinates vary with simple harmonic motion. However, the Y coordinates are unchanged when the ship undergoes only pitching motion.

Yawing will cause the X and Y coordinates to vary in an analogous fashion. When the ship yaws through an angle ψ the X and Y coordinates of the Ith dipole relative to the initial unrotated position of the ship bow are given by

$$X(I) = -D \times [NDIP/2 - (NDIP/2 - I + 0.5)cos\psi] \quad (19a)$$
$$Y(I) = D \times (NDIP/2 - I + 0.5)sin\psi \quad (19b)$$

while the Z coordinates remain unchanged.

For combined pitch and yaw motion these relative dipole positions become

$$X(I) = -D \times [NDIP/2 - (NDIP/2 - I + 0.5)cos\phi cos\psi] \quad (20a)$$
$$Y(I) = D \times (NDIP/2 - I + 0.5)cos\phi sin\psi \quad (20b)$$
$$Z(I) = -D \times (NDIP/2 - I + 0.5)sin\phi \quad (20c)$$

It is interesting to note that the $Y(I)$ coordinate has a ϕ-dependence when the ship both yaws and pitches.

3. SHIP SIGNATURE SIMULATION IN HIGH SEA STATES

3.1 Ship Behaviour in High Sea States

Sea state provides a qualitative measure of the combined effects of sea surface motion and wind conditions [5], varying from zero for calm, mirror-like seas to 9 for hurricane conditions. The behaviour of a ship in high sea states will inevitably depend on the skill of the helmsman and also the sea handling of the specific ship. Thus estimates of amplitudes and frequencies for roll, pitch, and yaw motions are likely to be subject to large uncertainties.

The RAN has provided some observational data concerning FFG, DDG and DE ship motions in high sea states [6]. These observations indicate that in sea states 7/8 (full gale conditions) :

(1) A roll amplitude of 18°, with a period of 10 s has been observed for unstabilized ships. This can be reduced considerably with fin stabilizers.

(2) Pitch amplitude is typically 6°. The natural pitch period is 5 s but actual pitch period corresponds to wave encounter period and can be up to 50 s.

(3) Yaw amplitudes are typically 5° – 10° in sea states 5 and above. This can be reduced to 2° in the hands of a skilled helmsman. The period appears to correspond to the encounter with each 7th wave and can vary from 10-50 s depending on heading relative to the waves.

To study the signature variation in high sea state from that in sea state zero the following representative parameter values were chosen:

(1) Roll amplitude 18° ; period 10 s

(ii) Pitch amplitude 6° ; period 20 s

(iii) Yaw amplitude 2° ; period 20 s

These values imply a comparatively large roll motion superimposed on to smaller pitch and yaw motions which occur at only half the roll frequency. The other parameters in the simulation are α, β, γ, and δ. The first two, α and β, were set to 1.0 assuming that the induced magnetization in the X and Z directions is of similar magnitude to the permanent magnetization. The value of $\gamma = HZ/HX$ at the Sydney location is given by -52370nT/24550 nT $\sim$ -2.1 [7-8] (in the Southern hemisphere the vertical component of the earth's field is directed upwards and so is negative in the coordinate system used here, whereas the horizontal component points North and is positive). This value was used in the magnetic field calculations. The value of δ is determined by the ship geometry and is about 0.12 for a 120 m long ship (see Appendix).

3.2 Signature Variation in High Sea States

The roll, pitch, and yaw motions of the ship result in oscillatory variations to both the magnitudes and positions of the dipoles representing the ship's magnetization. These variations will manifest themselves in the physically measurable magnetic field at points in space around the ship. Thus to study the effects on ship signature the magnetic fields due to a moving ship undergoing rotary motions must be computed and compared with the steady-state signature, when the ship sails on calm seas with no additional rotary motion.

A set of 20 three-axis dipoles spaced 6 m apart which represents the magnetization of an artificial warship 120 m long was used to provide a generic model on which to perform simulations [2]. The first dipole is placed 3 m from the ship's bow while the 20th is placed 3 m from the stern with the dipole array assumed to be at the waterline level. The vessel modelled is roughly equivalent to a DE class destroyer.

The magnetic fields are calculated by summing the contributions from all the dipoles in the array. Computation of ship fields when the ship rolls, pitches and yaws is considerably more complicated than for the zero sea state simulation. At each time step both a new set of dipole moments and also a new set of dipole coordinates must be first determined. This has the effect of slowing the simulation.

In the present work, the fields were calculated in 0.25 s time steps as the ship's bow passed from 100 m before the closest point of approach (CPA) to the observation point to 200 m beyond the CPA. This provides for the ship's magnetic anomaly to be computed across $2\frac{1}{2}$ ship lengths. Initially the ship speed was set to 5 m/s. At this speed the transit time of 60 s is of similar order to the periods of the roll, pitch and yaw motions.

A program SHIPMOTION was written in FORTRAN 77 to perform the simulations on the MRL VAX-8700 computer. SHIPMOTION consists of about 1100 lines of code and runs interactively under the VAX/VMS operating system. Graphical output is provided using the subprogram PLOTEZ [9] which can send output to either a Tektronix-4010 compatible graphics terminal or to a DEC LN03 laser printer. A copy of the program SHIPMOTION and sample input may be obtained from the author on request.

In the following sections the effect of various parameters which are expected to influence the signatures are examined. These may be divided into two categories : the **geometric** parameters (depth, abeam displacement of the observation point relative to the ship) and the **kinematic** parameters (ship speed and sea state).

3.2.1 Signatures at 20 m Depth

Figs. 2-4 show the X,Y and Z components of the ship keel signature computed as a function of ship distance from the CPA. The effects of the roll, pitch and yaw motions and also the combined effects of the three motions (abbreviated by RPY) are shown separately in each figure using the parameter settings given above.

For the X field component (Fig. 2), the rolling and yawing motions have little effect. However the pitching motion has a significant effect changing the field magnitude by up to 100 % at a distance of 125 m. In contrast the Y component (Fig. 3) is strongly affected by each of the three motions which change the single-peaked structure into a multi-peaked field shape. The combined effect of the three motions is greater than any of the individual motions. As expected, roll motion, which has the smallest period of 10 s, adds the highest frequency oscillations to the magnetic field.

Figs. 4 and 5 show the variation with ship motion of the Z component (Fig. 4) and the total field (given by $(BX^2 + BY^2 + BZ^2)^{1/2}$) respectively. The Z field is strongly influenced only by pitch motion with the largest variations being in the 50-125 m region where the bulk of the ship crosses the CPA so that the computed field will be most sensitive to variations in ship magnetization The total field is generally dominated by the vertical (Z) field at this depth so it is also most strongly influenced by the ship's pitching motion.

The athwartships (Y) fields appear to be most strongly affected by the rotary motions for this model ship. Directly under the ship's keel the athwartships field depends only on the athwartships dipole moments : the MX and MY dipole moments produce field components in the $X - Z$ plane through the ship. Thus it is sensitive to admixtures from the longitudinal (MX) and vertical (MZ) dipole moments during rotary motion. For example, roll motion will considerably affect the athwartships magnetization by mixing in the larger vertical permanent dipole moments with the smaller athwartships dipole moments.

3.2.2 Keel Signatures at 50 m Depth

Figs. 6 and 7 show the Y and Z field components due to the model ship at a depth of 50 m. Comparing Figs. 4 and 7 it is apparent that the vertical field is less affected by the intrinsic ship motion at greater depths than at shallow depths. In particular, pitch has a relatively smaller effect at 50 m because the pitching of the dipole array is relatively less significant at 50 m depth than at 20 m. For the 120 m ship a pitch amplitude of 6° implies that the bow and stern will pitch up and down by about 60sin6° $\sim$ 6 m. Since the dipole fields have an inverse cube variation with distance this will have a big effect on the signatures at 20 m depth but only a small effect at 50 m depth.

In contrast the Y field component is still strongly affected by the ship motion at 50 m depth with the relative contributions from each motion being roughly similar. Roll and yaw motion contribute strongly while the effects of pitch are less pronounced.

3.3 Effect of Depth and Abeam Displacement

As noted in the previous subsections the signature variation has a dependence on the depth of the reference point below the ship. Similarly it should depend on abeam displacement. Intuitively, at greater depths and abeam displacements the effects of ship motion should be less apparent because the relative motion of the dipoles from their equilibrium position will be less significant.

To obtain a qualitative estimate of how the ship signature behaves at high sea states the percentage root-mean-square (rms) deviations can be calculated. The rms deviation from the zero sea state signature is given by :

$$RMS\ deviation = \sqrt{\sum_{J=1}^{N} [BMotion(J) - BSteady(J)]^2 / N} \tag{21}$$

where $BMotion$ and $BSteady$ are the field values in high seas and calm seas respectively and N is the number of time steps in the simulation as the ship travelled the 300 m range past the observation point. The percentage rms deviation is defined as

$$Percentage\ RMS\ deviation = 100 \times \frac{RMS}{\sqrt{\sum_{J=1}^{N} BSteady(J)^2/N}} \tag{22}$$

With this definition the percentage rms deviations for the keel field components observed at different depths are given in Table 1. The ship speed is set to 5 m/s.

Table 1

Percentage Deviation versus Depth for RPY Motion

Depth (m)	X	Y	Z	Total
20	28	37	21	22
30	20	29	16	16
40	16	25	14	14
50	13	23	14	12
60	12	22	13	11
70	12	21	13	11
80	11	21	13	11

With the exception of the athwartships field, the field components and also the total field variations from sea state zero are less noticeable at greater depths. Following a similar procedure for abeam displacement the rms signature variations for abeam displacements in the range 0-50 m are given in Table 2 for a fixed depth of 20 m.

Table 2

Percentage Deviation versus Abeam Displacement for RPY Motion

Abeam (m)	X	Y	Z	Total
0.0	28	37	21	21
10.0	17	22	13	13
20.0	10	17	10	7
30.0	8	14	10	6
40.0	7	11	12	6
50.0	7	10	15	6

As might be expected the X,Y, and total fields each show less variation as the abeam displacement increases. The vertical (Z) field shows a greater relative deviation at abeam distances of 40 and 50 m than at 30 m. However the rms Z field value is only 59 and 37 nT at 40 m and 50 m abeam respectively and the absolute rms deviations 7 and 5 nT so that the overall effect on the Z field is slight.

3.4 Signature Variation with Ship Speed

Since the RPY motions are all time-varying the speed of the ship will influence the extent to which its magnetic signature is affected. If the ship passes a given point slowly then it will intercept a large number of wavefronts for a given distance travelled so that its motion and hence its signature will be considerably affected. On the other hand if the ship is travelling at a greater speed then it will intercept fewer waves for the same distance travelled so that its signature should be less affected.

Since the athwartships (Y) field component is most affected by the ship motions, it was selected as most suitable to test the influence of ship speed. Figs 8, 9 and 10 show the Y field at 20 m depth for ship speeds of 2.5, 10 and 20 m/s respectively. Clearly the ship speed strongly affects the ship signature in rough seas. The 2.5 m/s Y field is highly oscillatory and bears no resemblance to the steady-state field component. However, at 10 m/s, the Y field is far less oscillatory, whereas at 20 m/s the overall effect of the rotary motions is a displacement of the peak by about 30 m. Table 3 gives the percentage rms deviations for the keel field components compared with the same components in calm seas.

Table 3

Percentage Deviation versus Ship Speed for Each Motion
for Athwartships (Y) Field Component

Speed (m/s)	Roll	Pitch	Yaw	Combined
2.5	15	19	14	40
5.0	15	16	12	37
10.0	15	19	8	37
20.0	20	15	7	26
40.0	12	27	18	61

Under these criteria, the effects of the individual motions show no strong trends for the athwartships field. However the strong oscillations noted at low speed (see Figs. 3 and 8) are considerably reduced at higher speeds such as shown in Fig. 10 for 20 m/s. It should be noted that the definition of percentage rms deviation does not differentiate between positive and negative fluctuations between the zero sea state and high sea state signatures.

The rms deviations for each of the three field components and also the total field are plotted as a function of ship speed in Fig. 11 for the combined effects of roll, pitch, and yaw. These results show a clearer trend : the deviations become smaller up to speeds of about 20 m/s as expected. However at greater speeds the signature deviations increase again. At 40 m/s the ship transit time across the 300 m distance is only 7.5 s, whereas the periods of the intrinsic rotary motions are 10 and 20 s. Further it has been assumed that all the motions start in phase at time $t = 0$ with zero amplitude. Thus at a simulated speed of 40 m/s the ship signature experiences only part of the simple harmonic cycle for each of the motions.

3.5 Signature Variation with Sea State

So far the variation of individual components in a fixed high sea state has been compared with the same components in calm seas. To estimate the dependence of signature on sea state it is first necessary to relate sea state to the motion amplitudes. To a first approximation the periods of motion will depend on the ship's moments of inertia about each axis and so will be independent of the sea state

Sea state shows a roughly linear dependence with wind speed. Assuming that all the motion amplitudes vary linearly with sea state from zero at sea state zero to the values already used at sea states 7/8, the variation of the X,Y, and Z components can be computed by altering the roll, pitch, yaw amplitudes linearly. The resulting rms deviations for the keel signatures of the ship travelling at 5 m/s are plotted in Fig. 12 for sea states 0 to 9 and show a roughly linear dependency. The total field variation is not plotted since it is nearly identical to the vertical field variation.

The linear dependence with sea state is not surprising considering both the linear model assumed to describe ship motions and the linear variation of amplitudes with sea state. The deviations from linearity at higher sea states are probably due to the quadratic terms in the longitudinal and vertical magnetization in equations (14). It is interesting that even at low seas (SS 3/4) the ship motion has a significant effect (10-15 %) on the computed fields. Such seas are commonly encountered in Australian coastal regions [10-11].

4. CONCLUSIONS

The effects of intrinsic rolling, pitching, and yawing motions on the magnetic signature of a ship constructed mainly of ferromagnetic material have been simulated for high sea states assuming a simple dipole model representation of ship magnetization. These motions, assumed to be simple harmonic, were shown to impart a time dependence to the components of the ship's magnetization. In consequence the ship magnetic fields acquire additional oscillatory components in comparison with the zero sea state signatures. For the keel signatures the athwartships (Y) component is most sensitive to the effects of these motion since it is only due to the athwartships dipoles.

The effects of the various parameters (depth, abeam displacement, ship speed, and sea state) which influence the observed signatures were studied by varying each in turn with the other parameters held constant. When the observation point is placed at large depths or abeam displacements in comparison to the CPA, the ship motions produced relatively less deviations than when it is close to the CPA. These deviations decrease more rapidly with abeam displacement than with depth for the generic ship modelled here.

As ship speed increases, the effect of ship motion tends to decrease in significance up to speeds of about 20 m/s. At higher speeds the results depend critically on the starting point (epoch) of the simple harmonic motions since the ship's transit time is of the same order as the periods of the motions.

Even in lower sea states (less than about sea state 5) the ship motion can have a considerable effect on ship signature, especially underneath the keel. This time-dependent effect will constitute a low frequency ($< 0.2\ Hz$) magnetic background. Eddy current effects resulting from ship motion in the earth's magnetic field will also give rise to a low frequency background of even less significance.

The simulations have been performed with the ship on a magnetic North heading for convenience but with no loss of generality. On other headings, such as North East, the description of ship magnetization will be more complex since , for example, the athwartships magnetization will include an induced component in zero sea state. However, similar results will hold for the effect of the ship motions.

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APPENDIX

MAGNETIZATION VARIATION WITH YAW MOTION

Since the ship is assumed to be travelling due magnetic North at time $t = 0$, there is no magnetization induced in the athwartships direction. All the induced horizontal magnetization is in the longitudinal direction. However when it yaws through angle ϕ, there will be finite magnetization induced along its Y axis. This induced athwartships magnetization can be determined analytically assuming that the ship geometry can be approximated by an elongated ellipsoid with major axis a and minor axes $b = c$.

Stratton [A.1] has solved analytically the case for a uniform dielectric ellipsoid embedded in a homogeneous medium with a parallel applied electric field. The electric polarizations when the applied field is parallel to both the major and minor axes are derived. By analogy similar results apply for the case of an ellipsoid of homogeneous isotropic material introduced into a fixed and uniform magnetic field. When the ship is on the magnetic North heading all the induced horizontal magnetization will be parallel to the ship's longitudinal axis and is given by

$$MX_i = \frac{kB_0}{\frac{abcA_1}{2\mu_0} + \frac{1}{\mu_1}} \tag{A.1}$$

where k is a constant, B_0 the external applied (earth) field, and μ_0 and μ_1 are the permeabilities of air (water) and the ship hull respectively.

In the extreme yaw case when the ship has yawed through 90° and is oriented magnetic East-West, all the horizontal induced magnetization will be directed along the ship's athwartships axis and will have value :

$$MY_i = \frac{kB_0}{\frac{abcA_3}{2\mu_0} + \frac{1}{\mu_1}} \tag{A.2}$$

A_1 and A_3 are integral functions given by [A.2]

$$\begin{aligned} A_1 &= \int_0^{+\infty} \frac{ds}{(s + b^2)(s + a^2)^{3/2}} \\ &= \frac{1}{a^3 e^3}\left[ln\left(\frac{1+e}{1-e}\right) - 2e\right] \end{aligned} \tag{A.3}$$

$$\begin{aligned} A_3 &= \int_0^{+\infty} \frac{ds}{(s + c^2)^2(s + a^2)^{1/2}} \\ &= \frac{1}{a^3 e^3}\left[\frac{1}{2}ln\left(\frac{i+e}{1-e}\right) + \frac{a^2 e}{c^2}\right], \end{aligned} \tag{A.4}$$

where $e = \sqrt{1 - \frac{b^2}{a^2}}$ is the eccentricity of the ellipsoid. Now since $\mu_1 >> \mu_0$ for a steel-hulled ship, the ratio of the maximum induced magnetizations reduces to

$$\frac{MY_i}{MX_i} = \frac{A_1}{A_3} \tag{A.5}$$

so that

$$MY_i = \delta MX_i \tag{A.6}$$

where $\delta = A_1/A_3$ is a constant determined only by the geometry of the ellipsoid. If the values $a = 60$ and $c = 12$ are substituted for the major and minor axes of the 120 m long model ship, then the induced magnetization for an anticlockwise yaw motion through angle ψ can be approximated by

$$MY_i' = -0.12 \times MX_i sin\psi \tag{A.7}$$

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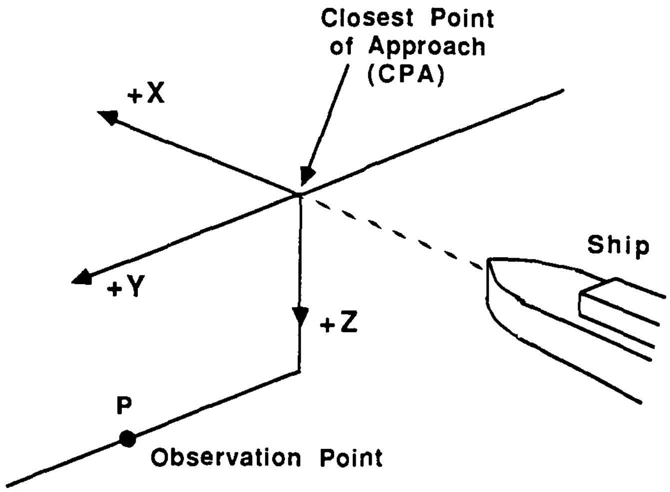

FIGURE 1 (a) Co-ordinate system used in the calculations.

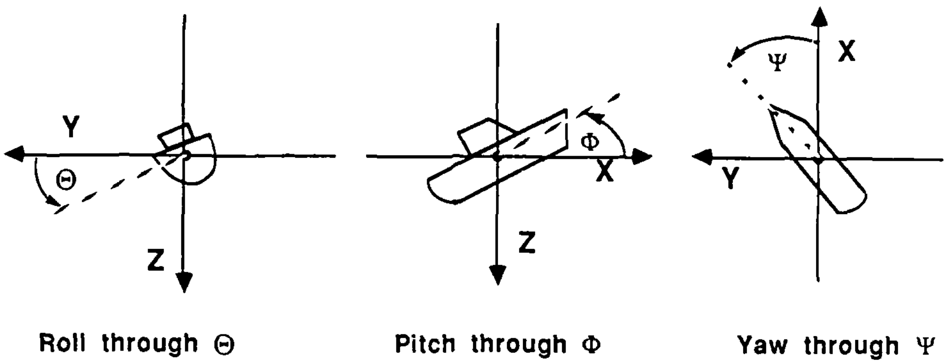

FIGURE 1(b) Roll, pitch, and yaw motions of ship.

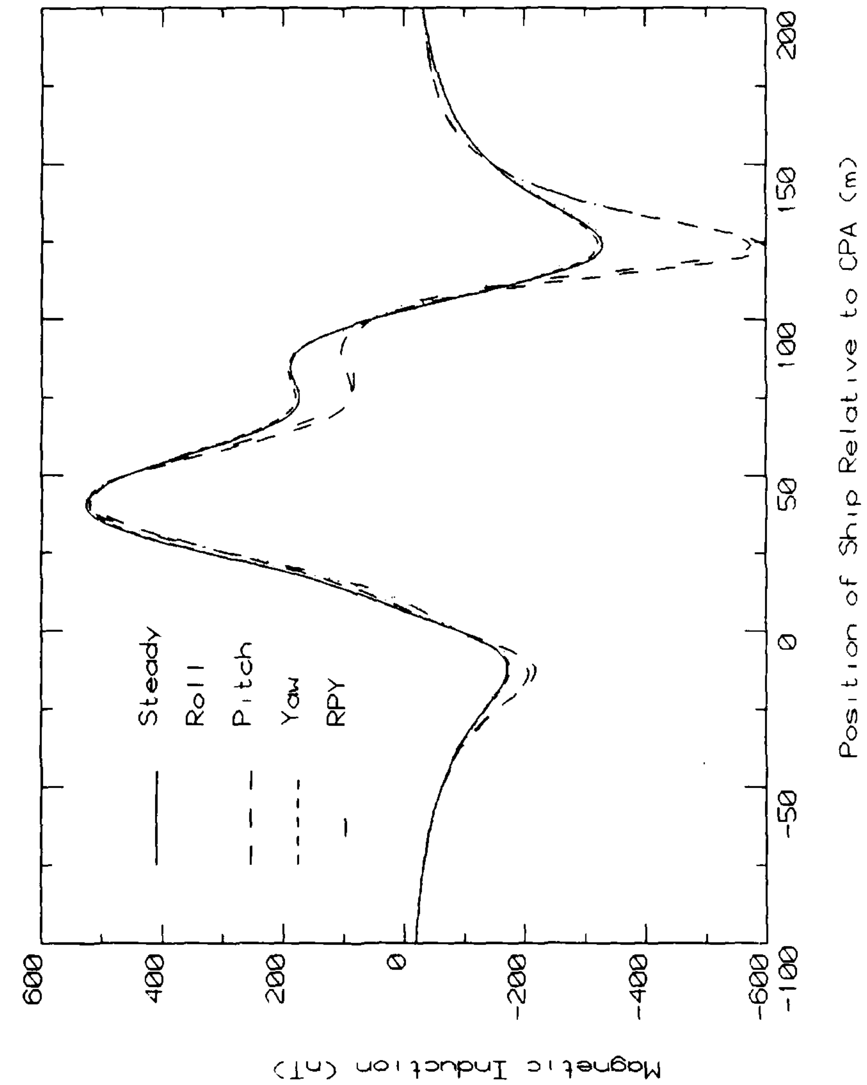

FIGURE 2 X-Component of keel signature at 20 m depth.

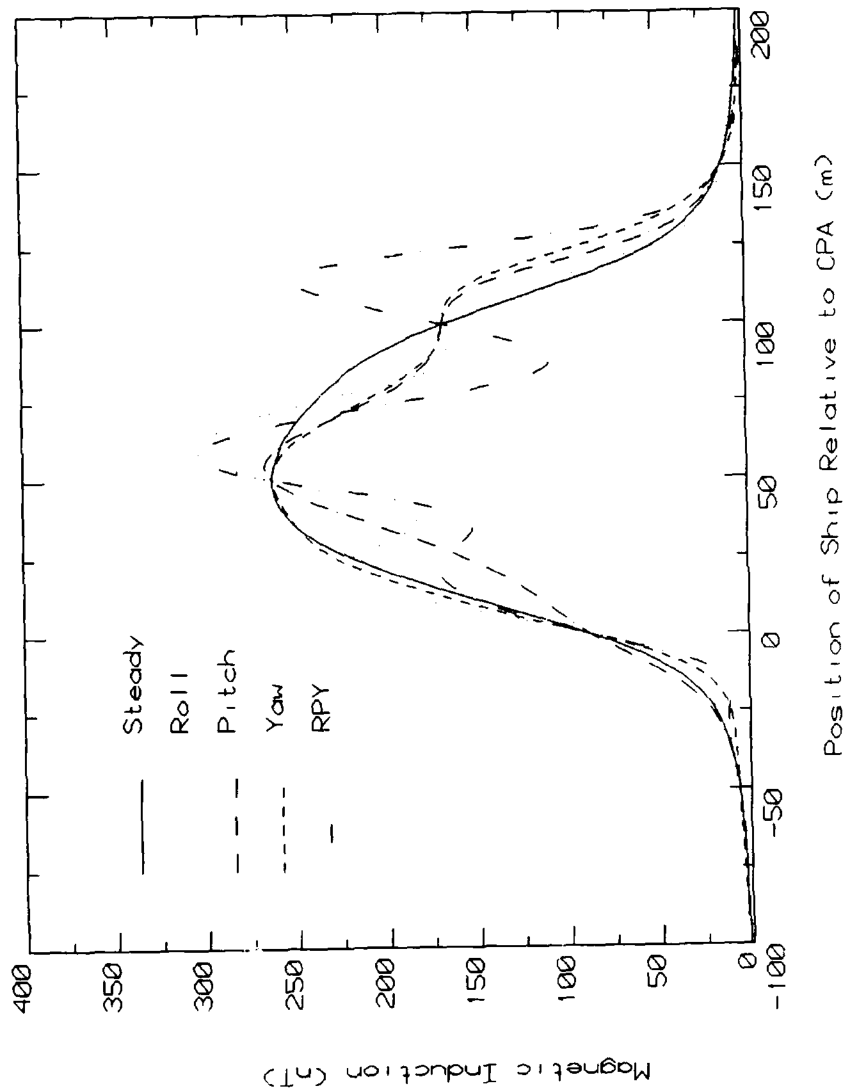

FIGURE 3 Y-component of keel signature at 20 m depth.

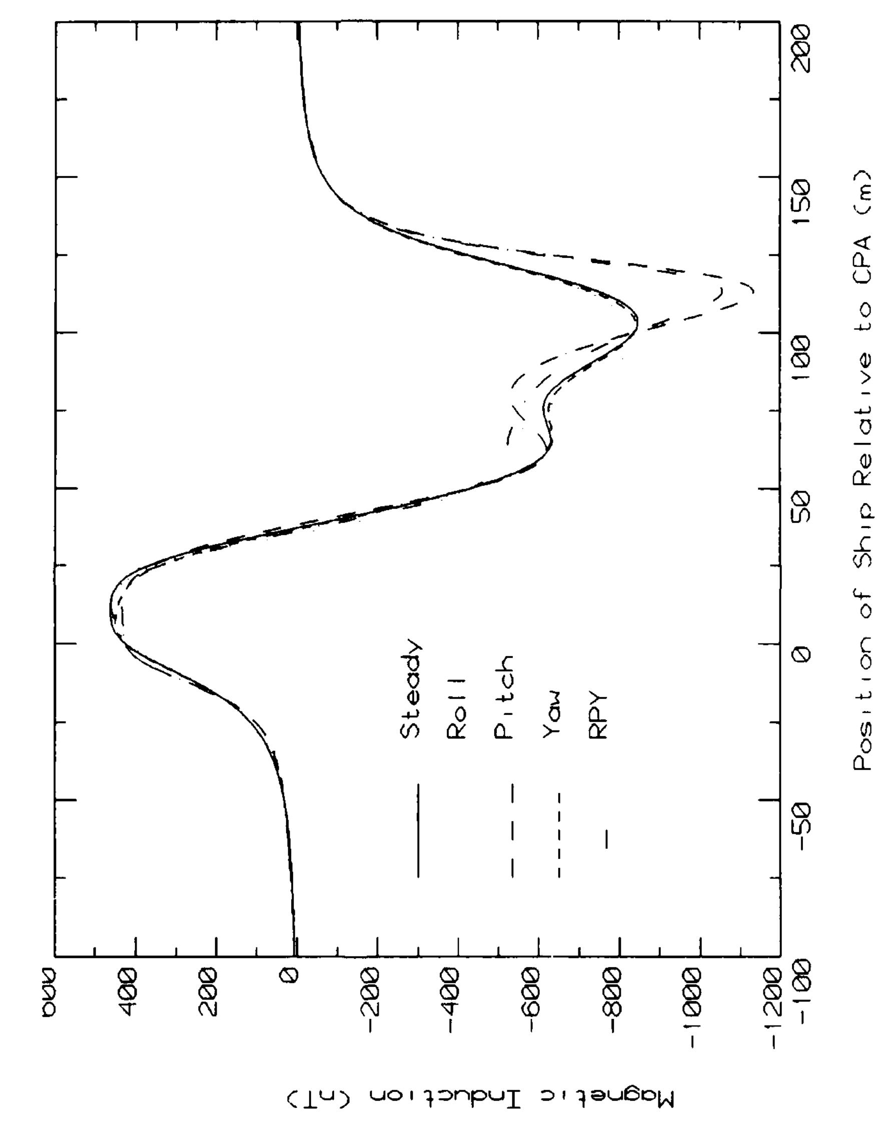

FIGURE 4 Z-component of keel signature at 20 m depth.

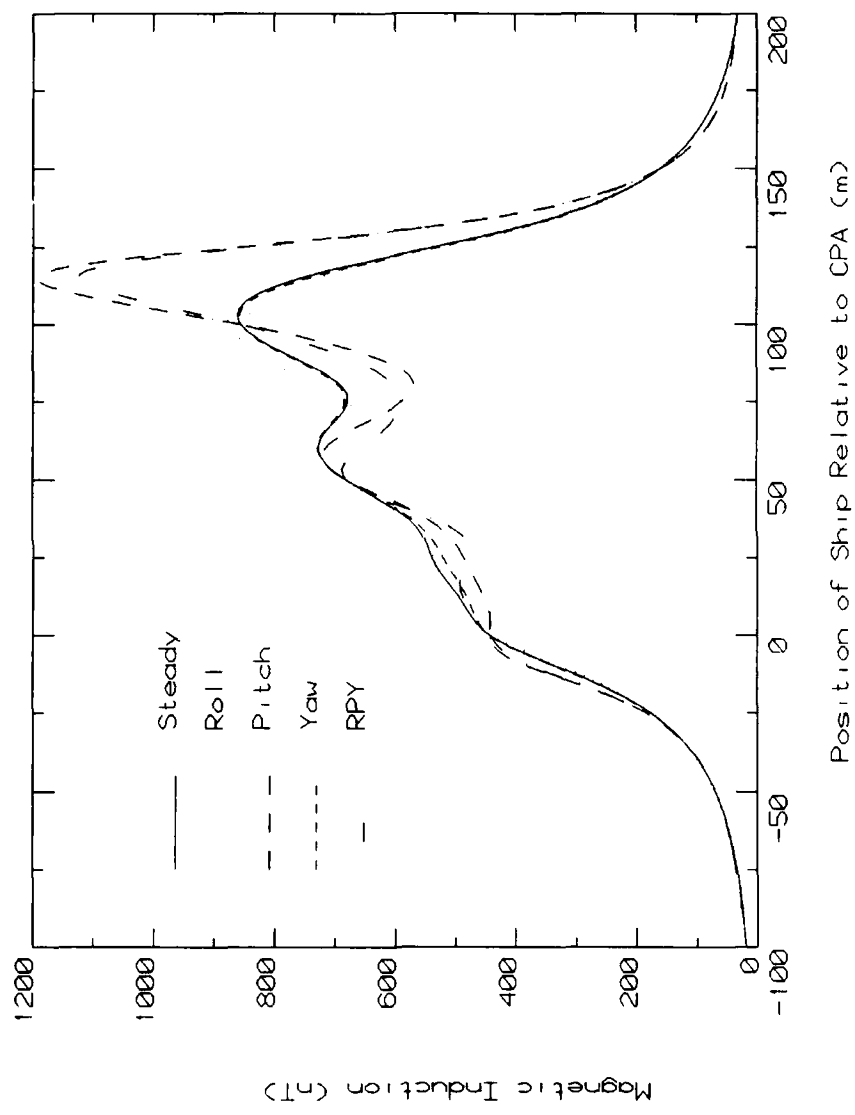

FIGURE 5 Total field keel signature at 20 m depth.

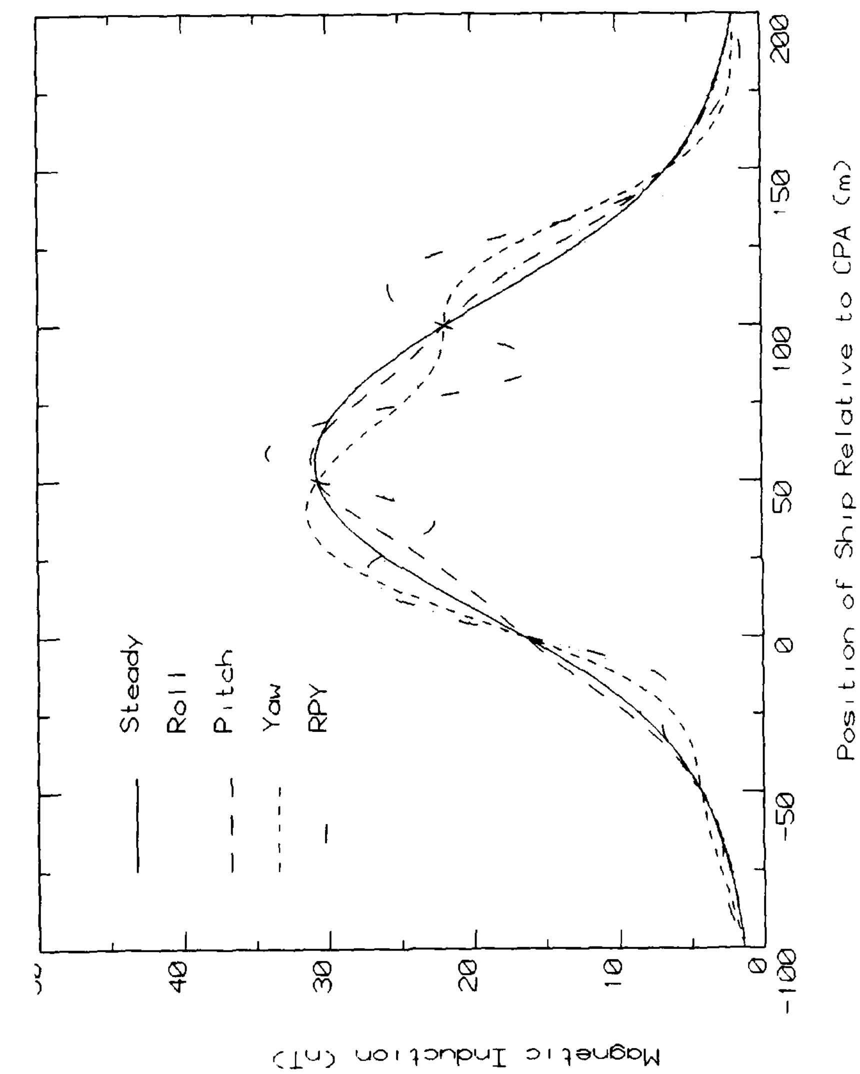

FIGURE 6 Y-component of keel signature at 50 m depth.

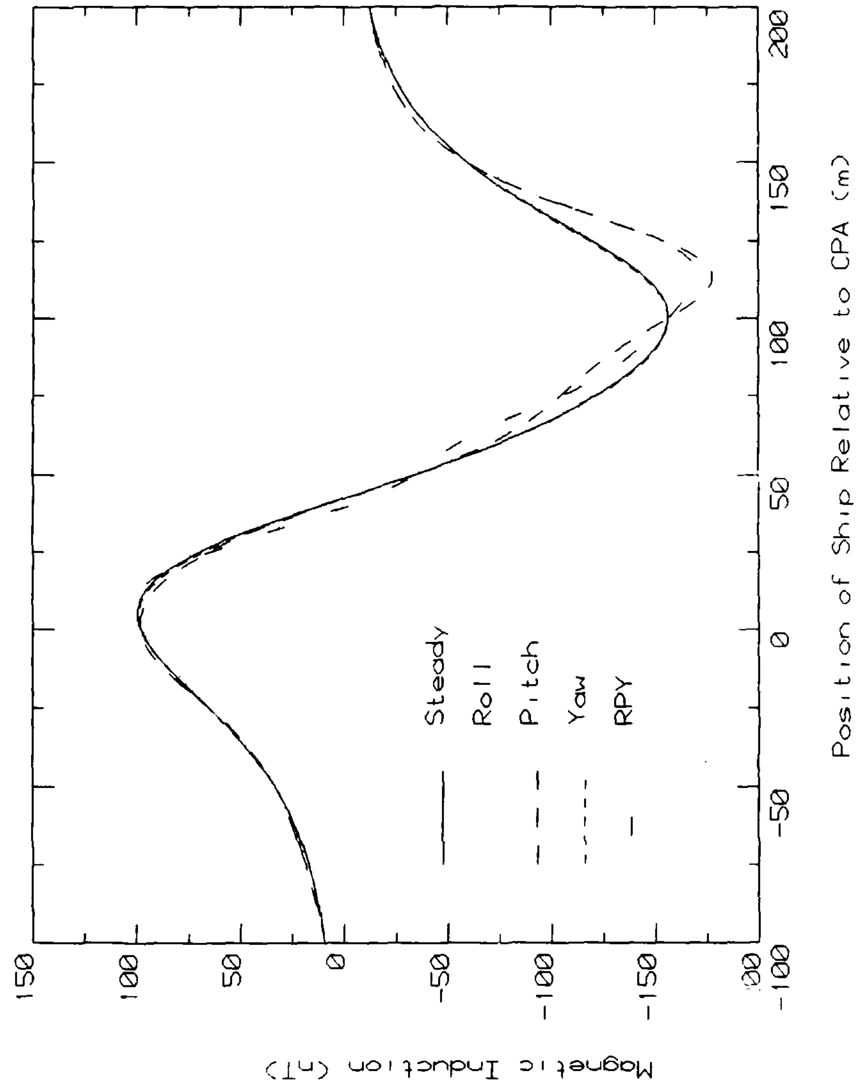

FIGURE 7 Z-component of keel signature at 50 m depth.

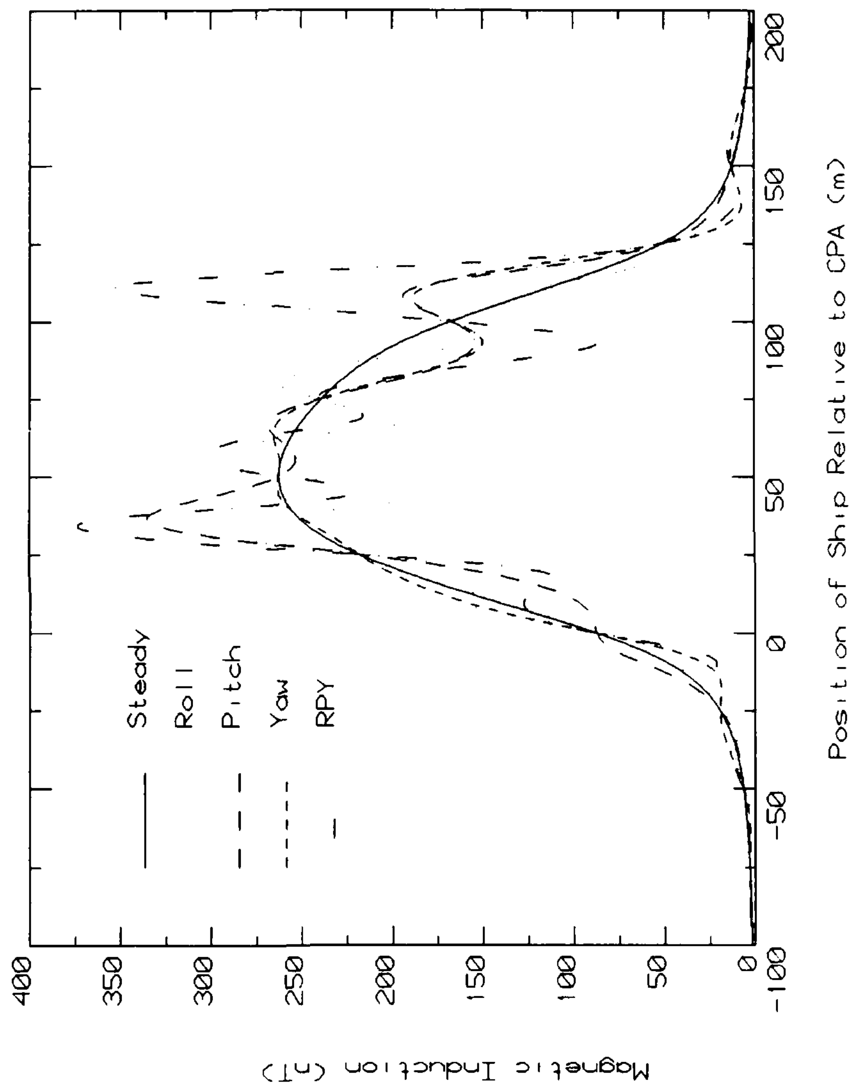

FIGURE 8 Y-component of keel signature for speed of 2.5 m/s.

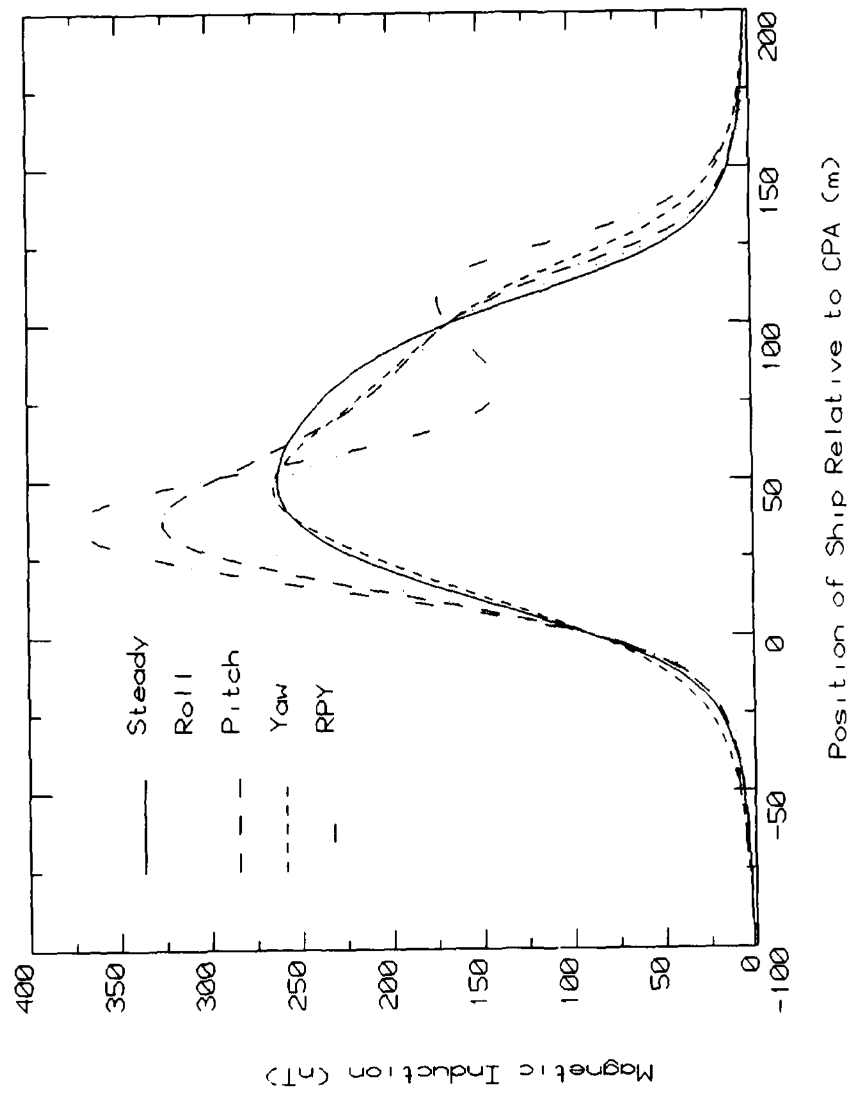

FIGURE 9 Y-component of keel signature for speed of 10 m/s.

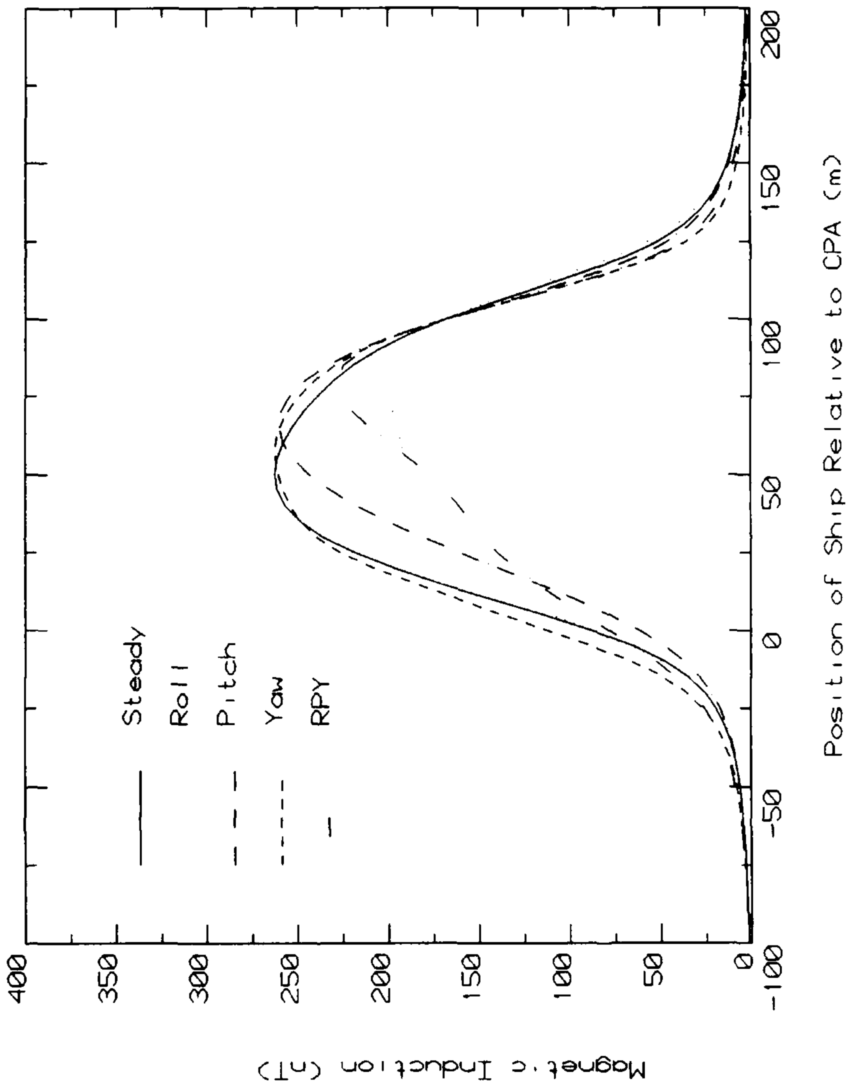

FIGURE 10 Y-component of keel signature for speed of 20 m/s.

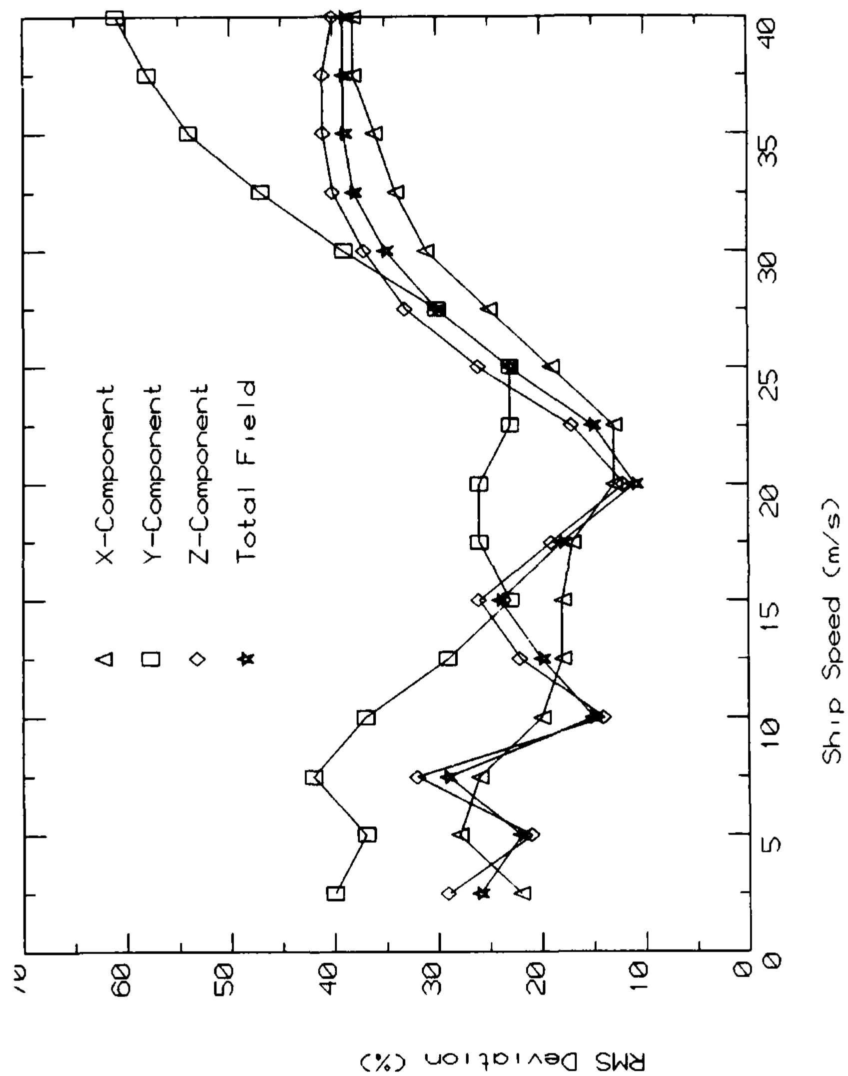

FIGURE 11 Variation of signature components with ship speed.

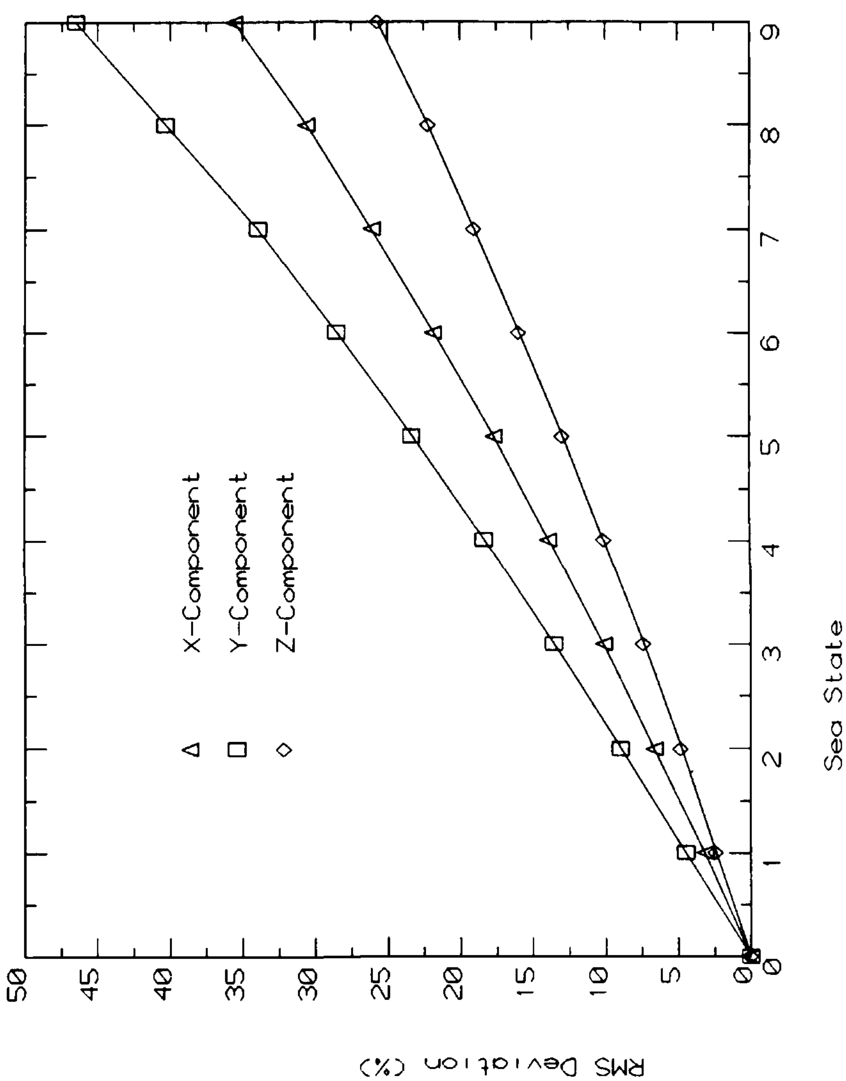

FIGURE 12 Variation of signature components with sea state.

SECURITY CLASSIFICATION OF THIS PAGE **UNCLASSIFIED**

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-R-1114	AR-005-225	Unclassified

TITLE

The effect of ship motion on ship magnetic signature

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REPORT DATE	TASK NO.	SPONSOR
May 1988	DST 85/153	DSTO

FILE NO.	REFERENCES	PAGES
G6/4/8-3532	11	32

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Chief, Underwater Weapon and
Countermeasure Systems Division MRL

SECONDARY DISTRIBUTION

Approved for Public Release

ANNOUNCEMENT

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KEYWORDS

Magnetic signatures Sea state Ship motion

SUBJECT GROUPS 0038

ABSTRACT

The effects of roll, pitch and yaw motions on a ship's magnetic signature are investigated. These three modes of rotary motion, assumed to be each simple harmonic, are treated as uncoupled and a dipole model representation is used to describe the ship's magnetization. Signatures are computed for a model ship assumed, for simplicity, to be bearing due magnetic North and compared with the steady-state signatures (for no rotary motion). Oscillatory magnetic field components result from these ship motions which decrease in significance, compared to the steady-state fields, as the observation point is moved further away from the ship's passage. These field deviations decrease more rapidly with abeam displacement than with depth. Variation with ship speed is more complicated and depends critically on the values assigned for the amplitudes, frequencies, and relative phases of the three modes of motion. In high sea states the magnetic signatures can vary considerably from those in calm seas with implications for magnetic-influence mine actuation.

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